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Magnetic behaviors of (Ga,Mn)As/Co_2FeAl Bilayers grown by molecular-beam epitaxy

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1. Introduction

As a model of diluted ferromagnetic semiconductors, (Ga,Mn)As has attracted a great deal of attention in recent years due to its potential to spintronic devices. However, the highest Curie temperature (T_C) of (Ga,Mn)As so far is 191 K, still well below room temperature for practical application [1]. One of the most promising ways to solve this problem is utilizing a magnetic proximity effect at the interface of ferromagnetic metal/ferromagnetic semiconductor heterostructures [2-4], which not only offers the prospect of combining metal-based spintronics with semiconductor spintronics, but also creates new functions and physical phenomena. In addition, the relative magnetization state of two magnetic layers can be controlled without the spacer layer as compared with the traditional magnetic devices, which brings us much benefit in technology application [5]. Recently, Olejnik *et al.* investigated magnetic properties of Fe/(Ga,Mn)As bilayers, demonstrating an exchange bias in (Ga,Mn)As film induced by antiferromagnetic coupling to the Fe film [4]. Heusler alloy Co_2FeAl is one of the most promising spintronic materials because of its high spin polarization and high *T*c. Recent studies have shown that epitaxial Co_2FeAl films grown on GaAs (001) have in-plane uniaxial magnetic anisotropy with an easy axis along the [110] direction, while for heavily Mn-doped (Ga,Mn)As films grown on GaAs (001), the easy axis is along the [1-10] direction [6]. Therefore, the investigation of Co_2FeAl/(Ga,Mn)As bilayers may offer an access to new functionalities in spintroncis and physical phenomena.

2. Experiments

In this work, we present a detailed examination of the structure and magnetic properties of (Ga,Mn)As/Co_2FeAl bilayers grown on (GaAs) (001) by molecular-beam epitaxy. The 150 nm-thick (Ga,Mn)As films with Mn concentration from 1 to 5% have been grown in one chamber of a molecular-beam epitaxy (MBE, V80) with two growth chambers. The growth rate and substrate temperature were 10 nm/min and 250℃, respectively. Subsequently the samples were transferred via a high vacuum channel to the other MBE growth chamber for Co_2FeAl evaporation. Reference samples were obtained by dipping Fe/(Ga,Mn)As into a HCl solution to remove Co_2FeAl layer. The well ordered surfaces were verified by *in situ* reflective high-energy electron diffraction (RHEED) observation. Finally samples were covered by a 2 nm-thick epitaxial Al layer to prevent oxidation. X-ray diffraction measurements and high-resolution cross-sectional transmission electron microscopy (HRTEM) have shown the single-crystalline structure of both layers as well as a sharp interface between them. Temperature dependence of the remanent magnetization showed T_C of the (Ga,Mn)As film is 80 K.

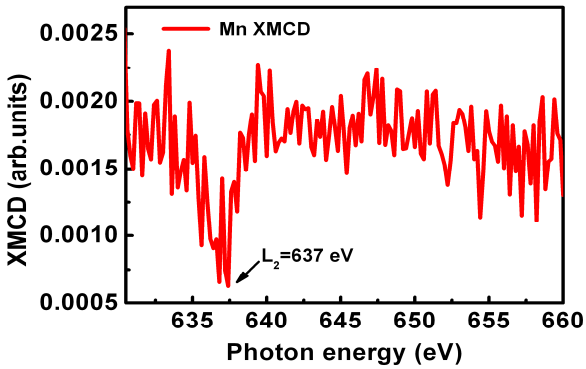

Fig.1 XMCD spectra of Mn $L_{2,3}$, normalized to the L_3 peak of the summed spectra for Co_2FeAl/(Ga,Mn)As bilayers.

We acquired x-ray circular magnetic dichroism (XMCD) spectra at the Co、Fe and Mn L edges at National Synchrotron Radiation Laboratory (Hefei, China). XMCD measurements have proved the ferromagnetic state of Mn element at the interface at room temperature, indicating magnetic proximity effect up to room temperature as shown in Fig. 1. The magnetic anisotropy axis of both Co_2FeAl and (Ga,Mn)As layers was determined by a superconducting quantum interference device

magnetometer (SQUID). Hysteresis loops of (Ga,Mn)As/Co_2FeAl bilayers were measured at 5 K under the external magnetic field along the [110] and [1-10] directions as shown in Fig. 2. It is noted that the magnetic behaviors of (Ga,Mn)As/Co_2FeAl bilayers strongly depend on the exchange coupling between them.

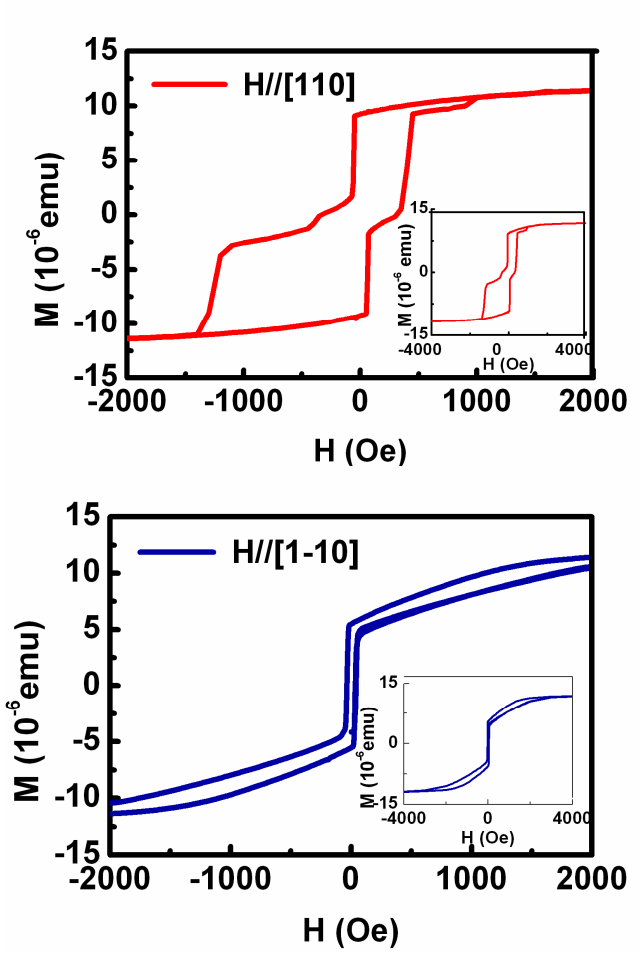

Fig. 2 In-plane hysteresis of Co_2FeAl/(Ga,Mn)As bilayers at 5 K. The external magnetic field was applied along the [110] and [1-10] directions.

3. Conclusions

(Ga,Mn)As/Co_2FeAl bilayers were well grown on GaAs (001) by molecular-beam epitaxy. Consistent with previous studies on Fe/(Ga,Mn)As of other groups, the interface layer of (Ga,Mn)As also remains spin polarized up to room temperature, which induced by heusler alloy Co_2FeAl. GaMnAs/Co_2FeAl heterostructures may be a good choice of MTJ. We also presented a detailed study on magnetic anisotropies of GaMnAs/Co_2FeAl bilayers.

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